Perception and Biodynamics in Unalerted Precrash Response

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ABSTRACT – This research seeks to better understand unalerted driver response just prior to a serious vehicle crash. Few studies have been able to view a crash from the inside—with a camera focused on the driver and occupants. Four studies are examined: 1) a high-fidelity simulator study with an unalerted intersection incursion crash among 107 drivers; 2) four crashes from the Virginia Tech Transportation Institute (VTTI) 100 car study; 3) 58 crashes from vehicles equipped with an event triggered video recorder; and 4) a custom-designed high-fidelity simulator experiment that examined unalerted driver response to a head-on crash with a heavy truck. Analyses concentrate on decomposing driver perception, action, facial and postural changes with a focus on describing the neurophysiologic mechanisms designed to respond to danger. Results indicate that drivers involved in severe crashes generally have preview that an impact is about to occur. They respond first with vehicle control inputs (accelerator pedal release) along with facial state changes and withdrawal of the head back towards the head restraint. These responses frequently occur almost simultaneously, providing safety system designers with a number of reliable driver performance measures to monitor. Understanding such mechanisms may assist future advanced driver assistance systems (ADAS), advanced restraints, model development of advanced anthropomorphic test dummies (ATDs), injury prediction and the integration of active and passive safety systems.

INTRODUCTION

Understanding realistic driver response just prior to impact is not simple. Few studies have been able to view a crash from the inside—with a camera focused on the driver and passengers. Understanding how drivers respond to crashes has the potential to improve active and passive safety systems in real-time. Such information could be used to increase the intelligence of such systems, so that each activation is tailored to the specific driver and occupants.

Since the mid-1990s, there has been a marked increase in research on advanced driver assistance systems (ADAS). Designers develop active safety systems to either prevent car crashes or ameliorate their impact speeds. Drivers may be alerted to hazardous situations, or the system may take temporary control of the vehicle, for example pushing back on the accelerator pedal, providing a brake pulse or steering wheel input (Michon, 1993). Such systems can detect driver impairment such as fatigue (Heitmann et al., 2001), automatically regulate vehicle speed with intelligent speed adaptation (Carsten and Tate, 2005), detect lane position and curve speed warnings (Sayer et al., 2005), provide front-to-rear-end collision warnings and automated braking (Lee et al., 2002), maintain longitudinal control using adaptive cruise control, and alert drivers of an impending intersection incursion (Penney, 1999; Stubbs et al., 2003). Certain systems use on-board sensors such as radar to detect slow moving or stopped vehicles ahead, micro GPS to determine position relative to curves, or machine vision systems to detect lane position. Some ADAS systems also rely on infrastructure to transmit information about traffic state. Intersection collision warning systems, for instance, must use site-based data to work properly.

The ADAS time domain generally extends from the few seconds before a potential crash up to the moment of impact. Passive safety system designers such as the injury biomechanist and traumatologist, on the other hand, study everything from the moment of impact (e.g., deploying pyrotechnic restraints, etc.) through treatment at a trauma center, as well as injury outcomes. Historically, there has been no 'handover' of information from one specialty to the other as the driver crosses over the impact line. Figure 1 illustrates these two domains relative to the impact point.

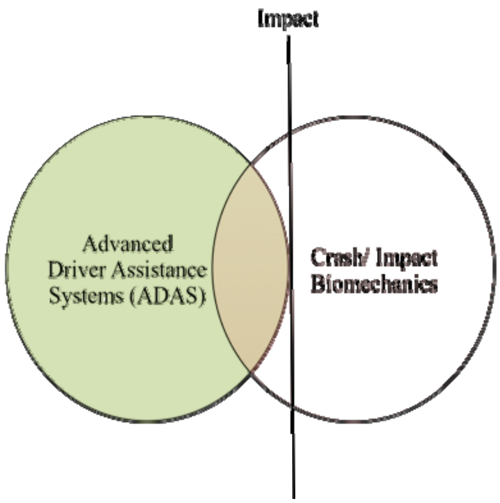

Figure 1. Sharing data across the impact barrier

In order for integrated safety systems to work most effectively, it is vital that specialists begin to share data across the impact barrier. For example, while ADAS systems currently alert the driver or provide some form of vehicle control automation, 'pre-arming' safety systems could further protect the driver against the consequence of a crash. By sharing data, we can move towards crossing the impact line and provide driver response information to passive safety systems. Specific information that could be measured in real time and fed into active and passive safety systems include the engagement of the driver in detecting a potential collision condition (e.g., braking or steering) or the amount of force being applied to the brakes or steering column.

Preview in crashes

Crashes can be roughly divided into one of two scenarios: the driver either has preview (is aware) that an impact is about to occur, or not. Where there is no preview or recognition that a crash is about to occur, the body is unable to trigger protection mechanisms (e.g., withdrawal from the impact/bracing) and respond to the danger. In this case, the body becomes a projectile, much like a crash dummy. While there are currently no references in the literature as to whether drivers know they will crash, preview is an important variable in understanding how and when a driver engages in a pre-crash response.

Objective

Pre-impact response and posture information could be particularly useful in the integration of airbag deployments, advanced restraint systems, future active and passive safety system integration and ADAS alert generation. Ability to predict injury and general occupant protection design could also be enhanced. While simple occupant position sensors for intelligent airbag deployments are now in limited production, they are largely based on static dummy models and do not consider reactive postures.

To address the current gaps in knowledge as to how drivers respond pre-impact in an unalerted state we explore the following questions:

1. Do drivers and passengers have preview of crashes, and if so, what responses do they exhibit?
2. How can safety systems detect preview from driver behavior?

METHODS

To begin to sketch out an operational definition of pre-crash driver behavior, four studies are analysed. The first three examine data from previous research including: 1) a high-fidelity simulator study with an unalerted intersection incursion crash among 107 drivers; 2) four crashes from the Virginia Tech Transportation Institute (VTTI) 100 car study; and 3) 58 crashes from vehicles equipped with an event triggered video recorder. In the fourth study, a custom-designed high-fidelity simulator experiment was conducted to examine unalerted driver response to a head-on crash with a heavy truck. This final study was specifically designed to address gaps in the knowledge identified by our analysis of the first three studies.

Analysis 1: Imminent intersection crash scenario

This first analysis examines and decomposes driver response to a simulated intersection collision-avoidance scenario. The study did not originally focus on pre-impact response. The data were collected as part of a US National Highway Traffic Safety Administration (NHTSA) research program to study driver responses to imminent crashes with and without antilock brake systems (ABS) (McGehee et al., 1996). The study was among the first to capture pre-crash withdrawal behaviors and was the inspiration for this overall direction of this research. Since this study was not originally intended to measure drivers' physical response to an imminent crash, there are a number of limitations associated with this analysis. First, there is no physical instrumentation on the subjects or explicit links to simulator sensor data (e.g., throttle, steering or brake data). Second, the data set is relatively old, with only videotape data intact. Nevertheless, the video is of sufficient quality to justify taking a first look here into this type of rarely recorded unalerted driver crash avoidance behavior.

Simulator

The Iowa Driving Simulator (IDS) was used for this study). Four multi-synch projectors create a 190-degree forward field-of-view and a 60-degree rear view. Motion cues are produced by a six-degree of freedom motion base. A fully instrumented vehicle cab is situated inside the simulator dome. The vehicle cab used in this study was a 1993 Saturn SL2. Four video cameras were also used to record driver behavior to the incursion event: one focused on the throttle and brake pedals; a second on the driver's face; a third on the driver's hands on the steering wheel; the fourth camera recorded the forward view of the road scene.

Subjects

One hundred and twenty drivers (60 males and 60 females) participated in this study. Subjects were recruited from the general public using a newspaper ad. To participate, subjects were required to hold a valid driver's license and to pass a general health screening.

Of the 120 videos examined, 56 males and 51 females (107 subjects total) between the ages of 25 and 55 years were selected for the analysis (video quality was poor for 13 subjects).

Experimental procedure

Several ruses were used to help ensure that subjects would not anticipate the intersection incursion event. First, subjects were informed that they would be driving for approximately 30 minutes (the drive was actually approximately 15 minutes in length). Second, subjects were told that their task was to assess the look and feel of the simulator and that they would be given a questionnaire on this topic after the drive. The combination of these two factors helped minimize the potential that the subject would expect a crash during the drive—a frequent expectation for simulator drivers.

In the scenario, one vehicle (a light truck) is stopped at a stop sign on the left side of the intersection while another (a Buick Regal) is stopped on the right side of the intersection.

At the time of the incursion event, there is no oncoming traffic. At the specified time-to-intersection, the vehicle on the right intrudes into the intersection, stopping with its front bumper at the center of the subject's lane of travel. Subjects had to perform evasive manoeuvres to avoid collision. After the intersection incursion event and the driver's response, subjects were instructed to pull to the side of the road and the simulation ended. Each subject experienced the incursion event only once.

The goal of the current analysis is to understand how drivers physically and emotionally responded to the unalerted imminent catastrophic crash. Subjects' reactions were captured via the four video angles. The two time-to-intersection incursion groups (2.5 and 3.0 seconds) of the original study were collapsed into one group, as both conditions provided an imminent crash condition.

As each video was analysed, specific behaviors were observed and noted. Several patterns emerged, and operational definitions were developed for each behavior relating to emotional and postural change. Ten different behaviors were observed in the 107 subjects. The behaviors and their corresponding operational definitions are presented in Table 1. Throttle release, braking and steering inputs were also scored. Behaviors described are not ordered in any way.

Table 1. Pre-crash response operational definitions

Driver Response	Operational Definition
Neck/head withdrawal	The upper cervical spine withdraws rearward during the pre-crash sequence.
Mouth cue/emotion	Emotional response to the imminent crash evident in the driver's mouth.
Lower back pressure	The lower back presses into the seatback during the pre-crash sequence. Associated with hard braking and hips rotating back.
Breath in	Observation of quick breath intake during startle reflex.
Neck extends	The upper cervical spine extends up towards the ceiling of the vehicle pre-crash.
Eyes widen	Eyes widening as the driver detects a hazard.

Steering wheel pressure/bracing	Driver squeezes the steering wheel during the pre-crash bracing action.
Leaning L/R	Upper torso lean away from the impact side.
Eyes closed	Eyes close just before impact.

Figure 2 shows the four views captured by the on-board video cameras. The video frame shows the face view camera in the upper left corner, the side profile/over-the-shoulder camera in the upper right corner, the foot camera in the lower left, and the forward view in the lower right (which shows an incurring vehicle that has pulled in front of the participant).

Examples of some of the observed behaviors illustrated in figures 2, 3, 4.

Figure 2. Simulator video views

The upper left quadrant of figure 2 shows the subject recoiling her neck/upper body and gritting her teeth in anticipation of the impact.

Figure 3. Mouth cue/facial expression in response to imminent crash

Figure 4. Steering wheel pressure/bracing behavior

Analysis 1 Results

The pre-crash responses are summarized in Figure 5. Each observed behavior was logged in a binary fashion—it either did or did not occur at some point after the intruding vehicle began to move and before the subject entered the intersection.

From the accelerator pedal video view, it was observed that the accelerator pedal was released by 100% of the subjects. Braking and steering also occurred in most subjects. Ninety-eight percent (n=105) braked $X^2(1, N=107 =99.15, p<0.0001)$ and 95% (n=102) steered $X^2(1, N=107) =87.94, p<0.0001)$ at some point during the response.

With regard to postural and emotional responses, over 90% (n=97) of subjects exhibited head/neck recoil $X^2(1, N=107) =70.74, p<0.0001)$ in response to the imminent collision. This was the most common physical response recorded in the analysis, followed by 54% (n=58) displaying a mouth cue/emotional response $X^2(1, N=107) =0.757, p=0.3843)$, and over 25% (n=28) exhibiting some sort of lower back pressure/rotation back into the seat.

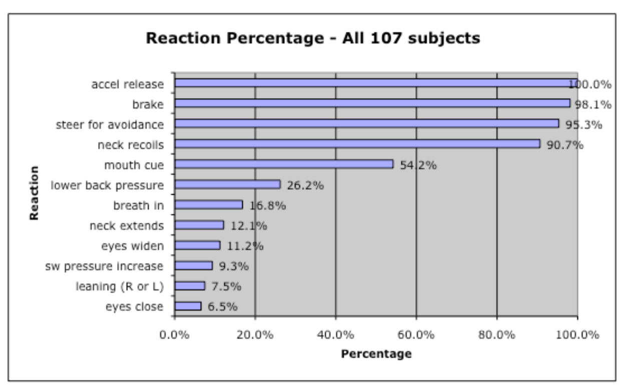

Figure 5. Percentage of response behaviors

The remaining behaviors were distributed among neck extensions (drivers extended the neck forward so as to orient themselves to the hazard), widening of the eyes, exerting pressure on the steering wheel, leaning left or right, or closing the eyes just prior to impact.

Analysis 2: 100 car study airbag crashes

In order to examine driver response to ‘real crashes,’ a second set of analyses were conducted on a unique set of video crash data. Some of the very first crashes ever recorded from inside a vehicle were captured in what is known as the ‘100 car study.’ Conducted by the Virginia Tech Transportation Research Institute (VTTI), this study was funded by the US NHTSA in 2006. As the first large-scale exposure study of its type ever done, it implemented advances in the miniaturisation of instrumentation so that multiple camera angles could be synchronised along with other vehicle data. Given the variability and complexity of driver behavior and performance, the random and rare nature of crashes, and the lack of adequate pre-crash data in the crash record, such real-world data collection is especially important.

To meet the 100 car study objectives, five cameras were distributed in vehicles:

1. Two cameras, one forward and one rearward-facing, were mounted from the rear-view mirror, capturing the forward view, the driver’s face and the view out the left side/rear of the vehicle

2. One mounted near the Centre High-Mounted Stop Lamp (CHMSL) and facing rearward

3. One mounted on the ceiling near the dome light, looking over the driver’s shoulder and showing their hands and feet. During daylight, it is possible to see foot and leg movement.

4. One mounted on the passenger side A-pillar and recording the right side of the vehicle.

After 12-13 months of driving in the 100 cars, VTTI collected data on approximately 2,000,000 vehicle miles of driving, including 15 police-reported crashes and 67 non-police-reported crashes. Almost all crashes were low-force and resulted in minor property damage only. Only four airbag-level crashes were recorded.

Analysis 2

This analysis sought to determine if pre-crash physical and emotional responses in these real-world crashes were similar to those observed in the initial intersection incursion simulator study.

Only video data was provided from the 100-car project. The airbag level crashes that were examined did show evidence of pre-crash response if there was preview. While the other crashes were also of interest, due to their mostly minor nature, none revealed any compelling pre-crash response.

Because there were so few crashes and each was of a different type (rear-end, crossing path, run-off-road, and frontal), this analysis takes the form of a case study. Quantitative analyses were not possible with such a small number.

The pre-crash response categories described in Table 1 are also used in this analysis. However, it should be noted that video angles are different here than in the intersection incursion study. Accelerator pedal or braking data were also not available for analysis, except in one crash where the driver’s leg could be seen moving during the response.

The video was recorded at approximately seven frames per second. While the motion video is quite clear in visualising the different responses, the still frames are a bit more difficult to interpret on a printed page. A time series that utilizes time-to-collision (TTC) is used. TTC is a useful measure for these analyses because it captures when each behavior occurs relative to the ultimate collision. Furthermore, it is commonly used in ADAS collision warning algorithms.

Results

Drivers from three of the four crashes showed evidence of preview. In the fourth crash (high speed frontal), the driver showed no evidence of preview. The three crashes with preview show pre-impact response behaviors similar to those observed in the IDS study. All drivers exhibited neck recoil, mouth cues, neck extension, eyes widening and some visible pressure on the steering wheel and bracing (Table 2). The top two most frequently observed behaviors were neck recoiling and an emotional mouth cue. The lower back pressure variable observed in the first study could not be assessed here with the available instrumentation or video views. As mentioned, however, driver leg position is visible in the second airbag crash.

The only behavior present in the first study that was not observed here was that of the eyes closing just prior to impact. This was most likely due to the lower video recording frequency in the on-board video (about 7 Hz) compared to the simulator (30 Hz).

Table 2. 100 car study driver response behaviors across airbag crashes with preview

Driver Response Behavior	Crash 1	Crash 2	Crash 3
Head and neck withdrawal	✓	✓	✓
Mouth cue	✓	✓	✓
Lower back pressure			
Breath in			
Neck extends	✓	✓	✓
Eyes widen	✓	✓	✓
Steering wheel pressure/brace	✓	✓	✓
Leaning right or left		✓	
Eyes closed			

Analysis 3: Event-Triggered Video Recorder (EVTR) Crashes

A third analysis examines data collected on a relatively new technology known as 'event-triggered video recorders' or ETVRs (Figure 6).

Figure 6. DriveCam ETVR

Such devices buffer video 24 hours a day and only record/write data if there is a lateral or longitudinal acceleration greater than approximately 5 m/s^2 (0.5 g). They have been used to provide feedback to younger drivers (McGehee et al., 2007a; 2007b; Carney et al., 2010) and in commercial vehicle fleets. While only about 50 ETVR systems have been used in research studies on younger drivers, thousands of such systems have been employed in fleets of taxicabs, limousines, ambulances, passenger car and other light truck fleets. The system has not been used as part of any formal research beyond the teen driving studies. One by-product of ETVRs is a record of crashes. These systems capture the context and the causes of the impact, as well as the possibility of revealing how injuries occur.

The ETVR made by DriveCam (Figure 6) is a palm-sized device that integrates two video cameras (forward and interior view), microphone, two-axis accelerometer, a 20-second data buffer, an infrared illuminator for lighting the vehicle's interior in darkness and a cellular transmitter. The device is mounted on the windshield behind the rear view mirror. The driver's upper body and face responses are visible. Passengers can also be seen to a limited degree (Figure 7).

Each video clip captures the 10 seconds before and 10 seconds after the threshold exceedance at a video capture rate of 4 Hz. DriveCam uses thresholds that roughly correspond to *g*-forces (+/- 10 percent). These thresholds refer to accelerometer readings that reflect changes in vehicle velocity or the lateral forces acting on the vehicle when cornering. If the acceleration exceeds 5 m/s^2 (0.5 g), then an event is triggered. Crash impacts also cause the system to trigger.

While the DriveCam ETVR only records video at four frames per second, it does provide an interesting view into the vehicle during a crash, as 80 still frames are available to examine during a pre-post crash impact sequence. A plot of the vehicle's lateral and longitudinal acceleration can also be viewed—revealing when a deceleration and/or steering response is initiated. Regardless of the video rate, these crashes are among the few ever recorded, and offer useful information for analysis. However, deeper investigation is challenging because of the limited camera view, frame rate, lighting and lack of vehicle performance parameters (e.g., throttle, brake, steering, speed, etc.).

For this analysis, DriveCam provided data on 53 crashes. An additional five crashes were analyzed as part of the University of Iowa younger driver research. Thus, a total of 58 'good' crash videos were examined. An additional 15 videos were examined but discarded due to poor lighting and resolution.

Subjects

Of the 58 crashes analysed, 33 involved male and 25 female drivers; there were also 11 male and 11 female passengers. Ages of the subjects were not available. Fifty-three of the crashes were from vehicle fleets: passenger cars, taxicabs, ambulances, and mini buses. An additional five crashes were in passenger vehicles of newly licensed novice drivers (16 year olds).

Analysis

While comparisons to the original set of variables from Table 1 were the goal, the quality of video and the video angles of the ETVR data were limited to a cabin view and a forward view. Data here, however, add the possibility of adding an estimation of driver control inputs relative to TTC. Such data can help determine whether the driver has changed his or her path by decelerating or steering. Passenger responses from video data that are clear and sustained (more than one frame) are also examined in a time series relative to TTC. Because these are largely categorical data, Chi-squared analysis was used where possible.

Results

Among the 58 crashes analysed, 71% (n=41) were frontal impacts (where the subject vehicle's front-end struck a vehicle or object off the roadway), 7% (n=4) were side-impacts (where another vehicle struck the side of the subject vehicle), 8% (n=5) were collisions involving being struck from the rear, and 14% (N=8) were either full or partial roll-overs (e.g., tipped onto side).

The first analysis examined whether the drivers and passengers had preview that a crash was about to occur. Preview was operationally defined as recognition by the driver or passenger that a threat has been detected. Preview responses generally included general facial expression change (e.g., mouth cue, eyes widening) and/or an acceleration change in the lateral and longitudinal data plots from the ETVR. Forty-seven of the 58 drivers (81%) and 19 of 22 passengers (86%) had preview that a crash was about to occur. A Chi-square test of these categorical data indicate preview was significantly higher than non-preview for drivers, $X^2(1, N=58) = 22.345$, $p<0.0001$) and passengers, $X^2(1, N=22) = 11.636$, $p=0.0006$).

Acceleration Change

Extracting the acceleration plots that the ETVR provides allowed for an analysis of when the vehicle began to decelerate relative to TTC. Deceleration observed from these plots occurred when the driver presumably released the accelerator pedal in the more minor deceleration cases and applied the brakes in the more urgent cases. While not as exact as a throttle sensor, this does give some indication of whether the driver had preview or not. Figure 7 is an example of how the deceleration trace was used as a marker. The pink line dips down at 1.25 sec TTC (the blue line is lateral acceleration). Also note the emotion state of the driver and passenger that coincides with the deceleration.

Figure 7. EVTR Acceleration change plot

Forty-two of the 58 drivers (72%) showed evidence of a deceleration during the response. A Chi-square test of these categorical data indicate deceleration was significantly more common than no deceleration, $X^2(1, N=58) = 11.655$, $p=0.0006$). Among the individual crash types, 33 of 41 (80%) frontal crashes showed evidence of deceleration, $X^2(1, N=41) = 15.244$, $p<0.0001$)]; 7 of 8 rollovers (88%) $X^2(1, N=8) = 4.5$, $p=0.0339$)]; one side and one crash struck from the rear showed a deceleration prior to impact. Statistical analysis was not possible on these last two categories due to the small numbers.

Facial state change

One of the most frequent early responses was change of facial expression exhibited by the driver and passenger (Figure 8).

Among all crash types, 42 of the 58 drivers exhibited a facial state change (72%); passengers responded with a facial state change in 19 out of 22.

Figure 8. Example of facial state change

crashes, or 86% of the time. A Chi-square test of these categorical data indicate facial change was significantly more common than no change for drivers, $X^2(1, N=58) = 11.655, p<0.0001$) and passengers, $X^2(1, N=22) = 11.636, p<0.0006$)

Head withdrawal

Among all ETVR crashes, 15 out of 58 (26%) drivers and eight of 22 passengers (36%) exhibited some sort of neck/shoulder withdrawal. A Chi-square test of these categorical data indicate head withdrawal was significantly lower for drivers, $X^2(1, N=58) = 13.517, p<0.0002$) and not significant for passengers, $X^2(1, N=22) = 1.636, p=0.201$).

Steering wheel pressure/bracing

Applying pressure to the steering column or other object by bracing just prior to a crash was examined next. Similar to head/neck withdrawal, bracing behavior was seen in significantly fewer drivers, 12 of the 58 (21%) [significant, $X^2(1, N=58) = 19.931, p<0.0001$)]. Although non-significant, a much higher percentage of passengers showed evidence of bracing relative to the drivers—fifteen out of 22 passengers (68%) [non-significant, $X^2(1, N=22) = 2.909, p=0.0881$)]. While a steering wheel was obviously not present for the passengers, they tended to press on the door panels and seats ahead (if seated in the rear).

Response timing

In order to understand response order and timing, a time series was plotted for each of the drivers and passengers that had preview. Deceleration was coded as a first response and facial change and steering were both coded as second responses (note that these responses can occur simultaneously with low frame rates). The timing of the first response among all drivers revealed that the mean TTC for the facial state change was 1.25 sec TTC with a SD of 1.05; accelerator pedal release/deceleration occurred at 1.37 sec TTC; steering at 1.7 seconds and withdrawal at 0.75 sec. As before, because of the overlapping responses, no reliable statistic could be applied to these data.

Analysis 4: Head-on crash experiment

The previous analyses focused on quantifying observed trends in pre-crash driver response from a simulator study and actual crashes. While these observations provide insight into how drivers respond *in general* just prior to a serious crash, they lack scenario control and precise evaluation of vehicle and driver response. They leave gaps with regard to precisely how pre-crash responses occur relative to each other. They were also limited by low-frequency video sampling and imprecise linking of driver and vehicle response data to the physical response.

Physical response in terms of head withdrawal and bracing could be further defined based on when muscles of the head/neck and fingers begin to change state. Facial state change, an apparently significant component of pre-crash response, might also be further defined. Systems that monitor fatigue and drowsiness via the eyes, for example, might be able to detect emotional state changes through eyes opening wider or squinting.

The objective of this final study was to determine driver response, posture and facial change relative to TTC and looming in a simulated catastrophic head-on collision with a heavy truck. Since emotional state change was previously a significant component to pre-crash response, the goal was to further decompose facial expressions. Similarly, head withdrawal was somewhat difficult to ascertain in the previous studies and was thought that with the simulator, muscular actions might be detected rather than simply physical movement of the head and neck.

In this study, vehicle control information (throttle, brake, and steering) was collected while surface electromyography (EMG) measured muscle response and video capture position and emotion. A variety of physiological measures have been used to assess driver performance (Lenneman, Shelley, and Backs, 2005; Michalski and Blaszczyk, 2004). Few studies, however, have examined muscle activity, driver response, posture, emotion, and vehicle control together during a simulated crash. Surface EMG has previously been used to study muscle fatigue (Katsis, Ntouvas, Bafas, and Fotiadis, 2004) and comfort issues in driving (El Falou, Duchene, Grabische, Hewson, Langeron and Lino, 2003) but not in pre-crash response.

Subjects

Five females and six males recruited from the general public and ranging in age from 24-49 participated in the simulator study ($\bar{X}$age =35.4; *SD*=7.7). Subjects received $25 compensation for the two-hour study, which included the installation of EMG instrumentation on selected muscle groups, calibration of the EMG, and the simulator drive. They were told that the purpose of the study was to understand postural issues during driving. This ruse was used so participants would not anticipate crashing during the study. The small number of subjects was due to financial constraints. Each subject required about three hours to complete the EMG instrumentation and calibration, drive and removal of EMG kit. Ten of the 11 subjects were instrumented with EMG. Technical problems prevented the final subject's muscle data from being collected. However, all other data were collected on the final subject.

Simulator

The University of Minnesota HumanFIRST driving simulator was used for this study. HumanFIRST is a partial-motion immersive driving environment simulator (DES) manufactured by Oktal. The DES is built around a 2002 Saturn SC2 full vehicle cab featuring realistic control operation and instrumentation, including force feedback on the steering and realistic power assist feel for the brakes. The visual scene is projected onto a high-resolution (2.5 arc-minutes per pixel) five-channel, 210-degree forward field of view with rear and side mirror views provided by a rear screen and vehicle-mounted LCD panels (Figure 9).

Figure 9. University of Minnesota HumanFirst Driving Simulator

The driving scenario was custom designed to put the subject in a catastrophic, head-on crash with a heavy truck. The custom-designed simulated roadway environment was a 15-kilometer undivided rural highway. Each lane was 3.6-metres wide, depicted standard roadway markings, and was both flat and straight. The scenario also included a 1.8-meter paved shoulder, an additional 6 metres of flat grass beyond the edge of the shoulder, and beyond that, fields and occasional farms.

Approximately 300 metres into the drive, a concrete barrier appeared on the right side of the subject's lane (Figure 10). The barrier prevented drivers from swerving onto the shoulder and away from the large (2.6-metre wide) heavy truck (Figure 10), thus forcing them into a direct centre head-on crash.

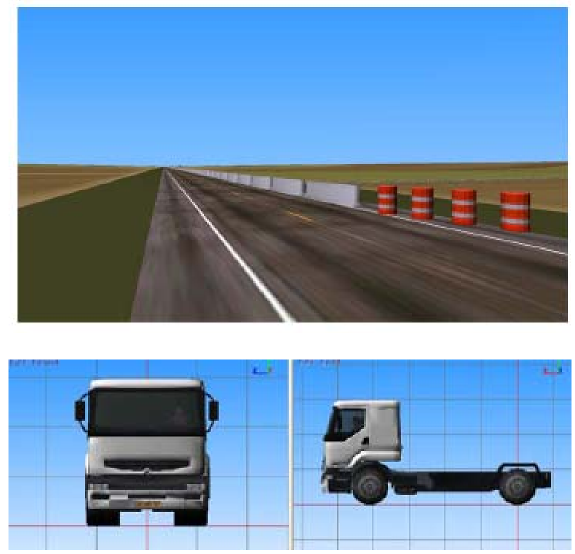

Figure 10. Roadway and truck used

Opposing-lane traffic consisted of a mix of small and large vehicles (cars, pickup trucks, and heavy trucks) spaced approximately 500 metres apart and travelling at approximately 90 km/h (25 metres/sec). Oncoming traffic was included both for realism and to reduce the likelihood that subjects would steer left into the oncoming lane to avoid the head-on crash.

Each subject drove for about five minutes so they could adjust to the feel of the accelerator, steering and braking. Previous research has shown that drivers adapt to simulators after just a few minutes of driving (McGehee et al., 2004). After the practice drive, subjects were directed to start the vehicle when instructed and drive down the roadway in their lane at the posted speed limit (90 km/h). As the 21st oncoming vehicle, a heavy truck, approached (approximately 180 seconds into the scenario), it suddenly and without notice swerved into the subject's lane. Two parameters influenced this event. First, the heavy truck moved into the subject's lane at 1.8 seconds time-to-collision as calculated between the subject and event vehicle speeds. Second, time-to-centre, the time it would take for the left edge of the heavy truck to reach the centre of the subject's lane was fixed at 1.8 seconds (Figure 11).

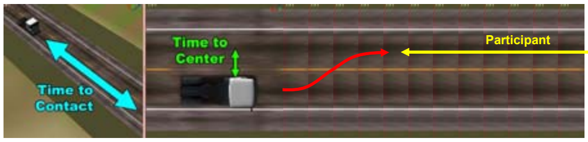

Figure 11. Swerve profile of heavy truck

Analysis

In order to understand the sequence and timing of responses to the heavy truck, an integrated time series visualization was used. The head-on crash was captured by a number of sensors that fed into three main data records:

1. Videos of driver actions from multiple vantage points. Video of the forward view, foot movements, facial expressions, hand positioning, and body posture changes were combined into a quad image to assure that the four videos were synchronized (Figure 12). Video was recorded at 30 Hz.
2. Driver actions, absolute vehicle state (speed, yaw rate, etc.), and the vehicle state relative to the environment (lateral position, distance to lead vehicle, etc.) were recorded in a time-stamped ASCII file. Each row represented a new time sample (20 Hz) and each variable was stored in a separate column.
3. EMG data was recorded by a separate computer at a much higher sampling rate (1000 Hz).

The video data were manually coded so that for each labelled relevant driver activity/expression/state, a data record was created with the starting and ending time. The experiment produced three time-stamped files, simulator driving record, and EMG recordings. Information from these files was then integrated for visualization.

Figure 12. Quad video image of forward view, facial view, over the shoulder view, and accelerator pedal

Results

Each of the videos was scored frame-by-frame in a time series to decompose the pre-impact driver actions and behaviors. We were particularly interested in determining if the same responses observed in the previous three studies were present.

The most frequently occurring response behaviors are ranked in Figure 13. Chi-square tests were also conducted to determine which behaviors were proportionally significant (i.e., the proportion of the response was greater than the non-response).

The most common responses to the head-on crash were accelerator pedal withdrawal, initial steering and head withdrawal, which occurred among all 11 subjects at some point during the pre-impact sequence (all subjects impacted the heavy truck). The next most common behaviors were braking and corrected steering (9/11 subjects; 82%). Each of these behavioral categories was significant. Several responses related to driver emotion were also detected: squinting of the eyes occurred in 9/11 subjects (82%) and was significant. However, the remaining responses—pushing back into the seat/bracing (8/11 subjects; 73%); opening the mouth (6/11 subjects; 55%); and others—were not significant. About half of subjects leaned back into the seat and/or turned their head to the side. Less common were utterances and eye widening.

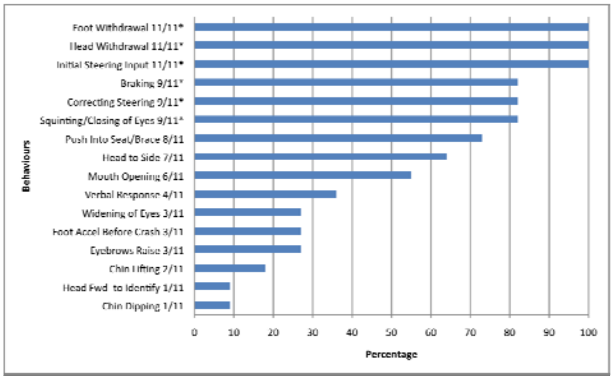

Figure 13. Percentage and significant (*) response behaviors

Behavior response timing

Time-to-collision (TTC) for the first response was examined across all 11 subjects and ranged from 0.77 seconds to 1.77 seconds ($\overline{X}$=1.11; *SD* 0.27 sec.) (Figure14).

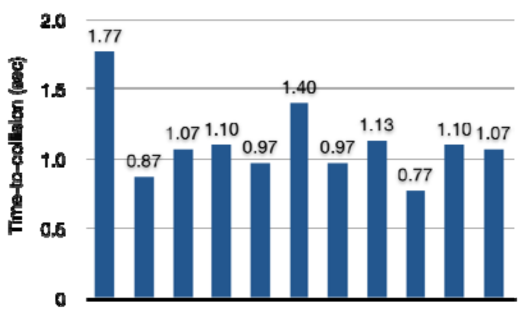

Figure 14. TTC of first response for all 11 subjects

DISCUSSION

This research has focused on identifying and decomposing *unalerted* driver responses in potentially catastrophic crashes. Previous psychological studies focused on driver perception and reaction have concentrated primarily on time to first vehicle control input, such as throttle release, steering or braking. Biomechanical research has generally concentrated on the structural aspects of injuries caused by impact. There is a gap between psychological and biomechanical research in the literature—due primarily to the lack of data on drivers in real crashes. Moreover, psychologically based research has not considered the psychomotor and biomechanical response of drivers during emergency maneuvres, while the injury biomechanics domain has not utilized high fidelity driver-in-the-loop simulation to measure the dynamic aspects of pre-impact response. Data now available from video-based crash recorders provides a never-before-seen view into injury mechanisms. This study attempted to cross these domains to determine what information could be used by both ADAS and passive safety designers.

Three of four studies examined here involved a post-hoc analysis of data already collected. Nine driver response behaviors were initially conceived as part of the Study one analysis (Table 1). Each analysis found some overlap in the timing of these core behaviors. The subset of data that were the most common among *preview* crashes were:

1. Accelerator pedal release
2. Steering
3. Braking
4. Head and neck withdrawal
5. Facial state change

When comparing the studies, a pattern emerged for the most common behaviors. Table 3 compares the statistically significant variables across all studies.

Accelerator pedal release was significant across all studies and was seen in all responses in the simulator studies. The VTTI 100 car study data did not have data available for this variable, but given the pre-view observed, it is likely this behavior occurred. The ETVR crash analyses show a deceleration in 80% of responses. The actual number may be higher, as the longitudinal acceleration plots provided tend to under-report acceleration.

Table 3. Statistically significant pre-crash behaviors across all studies

	Study 1 Intersection	Study 2 VTTI	Study 3 ETVR	Study 4 Head-on
Accel release	100%*	–	80%*	100%*
Steer	95%*	–	62%	91%*
Brake	98%*	–	–	82%*
Head withdrawal	91%*	100%*	26%	100%*
Facial change	54%	100%*	72%*	82%*

* p<0.05; (–) data not available for this variable

Steering was a significant variable in the simulator studies only. The VTTI data did not include steering information. While steering wheel activity was visible, only one (road departure crash) out of three drivers responded by steering for their crash type. Sixty-two percent of the ETVR crashes involved steering, but this was not significant. The varied crash types contributed to the lack of statistical significance. Steering is not always necessarily an appropriate response in crash avoidance. However, it can help detect whether a driver is engaged with a threatening condition.

Braking was also a significant component in the simulator studies. The VTTI data did not include braking information, but among the three crashes that had preview, all drivers appeared to be decelerating. The ETVR crashes also showed evidence of deceleration, but it was not clear whether it was accelerator pedal-based deceleration or brake input. For this analysis, the most conservative estimate is from accelerator pedal release.

Head withdrawal was observed in a significant number of crashes in the two simulator studies and the VTTI data. In the ETVR data, head withdrawal was present in only 26% of crashes. This again may be due to the great variation in crash types observed, since crash type affects response timing. The quality of the video was not high enough to estimate the looming properties of targets, so angular analyses were not possible. Despite the variability and lack of control in these studies, head and neck withdrawal figured prominently. The genesis of this human response can be linked closely to previous non-automotive collision research in infants, which showed the response is attributable to human sensitivity to looming information (Schiff, 1962; Bower, Broughton, and Moore (1971); Yonas, Petersen, Lockman, and Eisenberg (1980)).

Facial state changes were identified as a variable early in the analyses and were observed throughout the studies. Such facial state changes were significant in all studies except the intersection incursion study. A further attempt was made to decompose specific features of the face, including squinting, eyes closing or widening, and mouth changes. While most of these *individual* features were present across facial state changes, none were predicative enough for a trend to appear. Collapsing across each of these categories did reveal a significant trend, however. The head-on crash showed statistical significance for facial response (82%); among ETVR crashes, 72%; and 100% of the VTTI data showed evidence of a facial state change prior to impact.

The remaining variables (chin dipping, chin lifting, head to side, and bracing) were not significant in any of the studies. In the four analyses, steering wheel pressure/bracing was inconstant. The four studies varied widely for this measure (from 73% in the final head-on crash experiment to 100% in the VTTI preview-based crashes). The ETVR data showed that 22% and 68% of passengers braced; and 26% of the intersection crash responses showed evidence of bracing. The variability in these responses may relate to the amount of time the driver had before impact. It is possible that the less preview time available, the less time there is to physically prepare for impact. Decision-making for the driver may favor braking or steering before bracing in attempt to move away from the danger.

How these data could be used by designers

There are two potential safety domains where these data may be useful: among ADAS and intelligent restraint designers. Neither of these safety areas currently integrates dynamic real-time information about the driver or occupants into their algorithms. Both rely on standard estimates of behavior or posture.

ADAS system integration

ADAS systems range from detecting drowsiness and fatigue to adaptive cruise control and intelligent speed adaptation. The data examined here are likely to be most useful for ADAS systems that relate to collision warning and avoidance. Such systems issue an alert or intervene whether or not a driver has recognized a hazard. Triggering an alert or adjusting vehicle control after a driver is engaging in a response could interrupt and distract from the hazard. Thus, integrating the throttle position with a sensor system (e.g., radar) could minimize such a possibility. Predictable response measures also have implications for minimizing nuisance alerts in ADAS systems. One limit of current systems is that they do not integrate real-time driver response. Ideally, if a driver has already begun the process of responding in the form of an accelerator pedal release, steering or braking, alerts could be suppressed and system trust may be increased (Lee et al., 2002).

Adding a redundant driver response cue to such systems could also increase system effectiveness. Another reliable and early response of drivers in these crash conditions was a facial state change related to the emotional recognition of threat detection. Such facial feature changes could be integrated into current systems that monitor eye position (for distraction monitoring), drowsiness or fatigue. Ekman et al., (1994) developed a standard set of 'Universal facial expressions' (anger, happiness, sadness, surprise, dislike and fear). They further developed a set of physical landmarks and movements that define the face by a series of 'action units.' Each action unit has some related muscular basis (Figure 15).

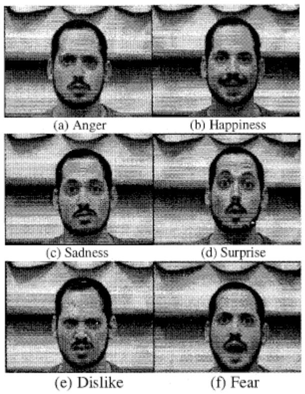

Figure 15. Six facial categories (De Silva et al., 1997)

Computer vision systems can automatically determine these landmarks and detect subtle facial movements. Azcarate et al., (2005) created a real-time and dynamic facial expression recognition system to specifically track such changes. They defined facial 'displacement vectors' that could determine the directionality of different emotional state changes. Figure 16 shows how such displacements are tracked from video.

Figure 16. Facial landmark recognition from Azcarate et al. 2005

Intelligent restraint integration

In terms of passive safety, data from this study could potentially help restraint designers develop more intelligent triggering mechanisms. Intelligent restraint systems might account for occupant age, gender, weight, sitting position, as well as the severity of the collision (Mackay et al., 1998). Machine vision systems such as those described above could be used to sense posture. Pre-impact response information could help inform intelligent restraint systems that customize the pretensioning force. For example, if the driver has withdrawn his/her head back to the headrest, a different pretensioning force could be applied to retract less of the belt compared to a full pyrotechnic response.

While bracing did not occur as frequently as expected, it was present in all of the VTTI preview-based crashes, 73% of the head-on simulations, 26% of the intersection incursion simulations and 20% of the ETVR crashes.

Integration of driver pre-crash response with active and passive safety systems is key for future advanced safety architectures. Incorporating real-time driver response could enhance their effectiveness of passive systems such as motorized shoulder belt harnesses and head restraints by customizing the response of the impact countermeasure. Simply knowing a driver is in or out of position could radically change the way future airbags are deployed.

LIMITATIONS

While this study is among the first to examine pre-crash response from real crashes, there are a number of limitations that must be mentioned. First, the number of crashes analysed, both simulated and real world, were relatively few (58 real crashes and 118 simulated crashes). Moreover, the crash scenarios, as they come from naturalistic driving studies varied widely, including intersection incursions, crossing path crashes, roadway departure frontal crashes, and both front-to-rear-end and rear-end crashes. This variability diminishes the ability to capture physical response trends.

Another limiting factor was the frame rate of the video data. The simulator provided 30Hz video data, which is reasonable for frame-by-frame analyses. However, the real-crash video was limited to 4Hz in the ETVR data and 7Hz in the VTTI data. These analyses were challenging when trying to detect exact onset and subtle changes of the driver response. Because crashes develop in milliseconds, increased data rates and resolution are required to decompose driver response more precisely. While this is a limitation, it was observed that many pre-crash responses occur almost simultaneously anyway.

The number of video views in the real crashes were also limiting compared to the simulator data. This was particularly the case with the ETVR crashes where the steering wheel was not viewable. Moreover, the lighting and overall quality of the video made some response interpretations difficult. Video quality was also a limitation of the first simulator study where a number of response analyses were not possible.

Lack of detail in the vehicle-based data integrated with the video was also a limitation for the real-world crashes. Since the two simulator studies showed that throttle release was among the first driver responses, it would have been useful to have such coordinated information. Future naturalistic studies will have much more detailed information integrated into the video stream.

Our analysis suggests that driver response must be decomposed in terms of initial stimulus registration and resulting response prior to impact. Figure 17 presents tools for gathering data ranging from benchmark laboratory studies, with the most experimental control but the least realistic driver behavior, to naturalistic driving studies, which offer a realistic window into 'true' driver behavior but no control. Combining data from all of these tools will help paint a comprehensive picture of driver performance and behavior.

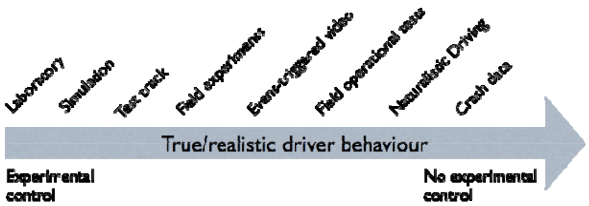

Figure 17. Range of driver performance tools.

CONCLUSIONS

This study showed that most drivers do have preview that a crash is about to occur, and have time to respond by decelerating and steering. Drivers and passengers often register a threat through an emotional state change, as well as by withdrawing their heads and necks toward the headrest. Only about 20% of drivers and 68% of passengers braced in anticipation of impact among the ETVR crashes. However, the three crashes from the VTTI analysis all demonstrated bracing; and in the head-on study, over 80% of drivers braced. Results also indicate that multiple behaviors can overlap and occur fairly quickly relative to the impact—sometimes just a few hundred milliseconds after the initial response.

Information about driver state just prior to an impact could be incorporated into both ADAS and advanced passive safety systems. A number of new technologies can integrate the vehicle control information (e.g., throttle state), driver posture, and facial emotion. Integrating such information into systems could result in fewer nuisance alarms and increase driver trust in such systems.

Finally, future biomechanically-based injury prediction models should include the integration of more sophisticated dynamic pre-impact muscular response (e.g., tensing and bracing) and posture. Understanding more fully muscle interaction effects on driver and passenger posture will help better predict injury in car crashes.

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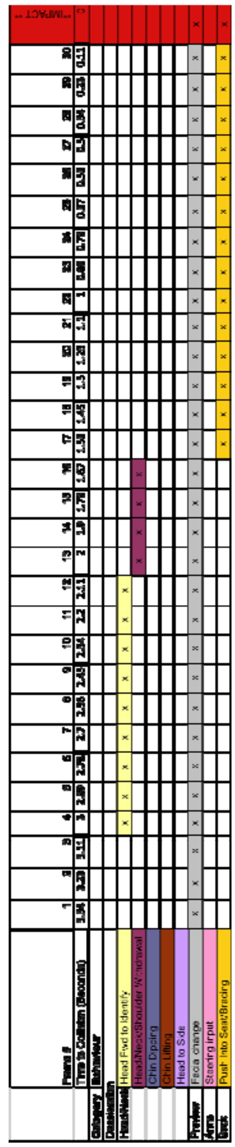
APPENDIX A

Example driver response time series for one of the VTTI airbag crashes.



Frame #	Time to Collision (Seconds)	Deceleration	Head/Neck: Head Fwd to Identify	Head/Neck/Shoulder Withdrawal	Chin Dipping	Chin Lifting	Head to Side	Posture: Facial change	Arms: Steering input	Back: Push into Seat/Bracing
1	3.34							x		
2	3.23							x		
3	3.12							x		
4	3		x					x		
5	2.89		x					x		
6	2.78		x					x		
7	2.7		x					x		
8	2.55		x					x		
9	2.45		x					x		
10	2.34		x					x		
11	2.2		x					x		
12	2.11		x					x		
13	2			x				x		
14	1.9			x				x		
15	1.78			x				x		
16	1.67			x				x		
17	1.56							x		x
18	1.45							x		x
19	1.3							x		x
20	1.28							x		x
21	1.1							x		x
22	1							x		x
23	0.88							x		x
24	0.78							x		x
25	0.67							x		x
26	0.56							x		x
27	0.5							x		x
28	0.34							x		x
29	0.23							x		x
30	0.11							x		x
IMPACT	0							x		x

APPENDIX B

EVTR time seroes example

	Frame #	[illegible]	[illegible]	7	[illegible]	[illegible]	[illegible]	11	12	**IMPACT**
	Time to Collision (seconds)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
Category	Behaviour									
[illegible]	Accel. Withdrawal/Braking		x	x	x	x	x	x	x	x
Head/Neck/Shoulder	Head Fwd to Identify									
	Head/Neck/Shoulder Withdrawal									
	Chin Dipping									
	Chin Lifting									
	Head to Side									
[illegible]	Lateral change			x	x	x	x	x	x	x
Arms	Steering input			x	x	x	x	x	x	x
Back	Push Into Seat/Bracing									

APPENDIX C

Head-on crash simulation time series

	Frame #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	Time (s)	0.93	0.90	0.87	0.83	0.80	0.77	0.73	0.70	0.67	0.63	0.60	0.57	0.53	0.50	0.47	0.43	0.40	0.37	0.33	0.30	0.27	0.23	0.20	0.17	0.13	0.10	0.07	0.03	0.00
Category	Specific Reflex																													
Legs	Foot Withdrawl	x	x	x	x	x	x	x													x	x	x	x	x	x	x	x	x	x
	Foot Accelerating																													
	Foot Braking																													x
Neck	Head Fwd to Identify																													
	Head Withdrawal										x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Chin Dipping																													
	Chin Lifting																													
	Head to Side												x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Face	Widening of Eyes																													
	Squinting of Eyes																				x	x	x	x	x	x	x	x	x	x
	Eyebrows Raise																													
	Mouth Emotion												x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Arms	Turn Wheel Away, Right								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
	Correcting Steering, Left																								x	x	x	x	x	x
Back	Push Into Seat																											x	x	x
Utterance	Initiation of Verbal Response											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x